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Extended exergy based ecological accounting for the transportation sector in China

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ABSTRACT

Extended exergy appears to be the only currently available second-law based and unified metric for ecological accounting, and it represents an effective measure of the technical, social and environmental impacts associated with the general "operation" of a complex society. The method of analysis is called Extended Exergy Accounting (EEA), and it was used in this study to assess the primary resource-based ecological cost of material and energy resources, human labor, capital contributions, and environmental impact of the transportation system in China on a 2008 database. Sub-sector distribution analyses are presented for the extended exergy cost by considering four modes of transportation (highways-i.c.e. powered, railways, waterways and civil aviation). A chemical exergy accounting of the cumulatively emitted CO, NOx and SO_2 was applied as a preliminary step required by EEA to assess the overall ecological impact of waste gas emissions by calculating an "exergetic avoidance cost". The results showed that natural input represents the largest portion of the extended exergy depletion in transportation sector (TR-sector), and highways require the highest extended exergy investment among the considered modes. In the conclusions, a few pertinent recommendations based on our results are put forth, to increase the understanding of technical-social-ecological energy depletion, to promote the operational efficiency in transport system, and to indicate the limits of current waste gas emission reduction measures, thus providing a holistic method and a systematic view and thus help decision makers to devise policies for a less unsustainable development and for a more rational environmental management.

Contents

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) 2007 report, climate change has become an issue of global

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concern, and global warming is an important problem affecting not only human development but the very survival of the human race [1]. This warming is directly linked to the increase in the atmospheric concentration of greenhouse gases (GHG). Waste gas emission mitigation, which is directly related both to fossil energy consumption and to GHG production, is an issue involving the natural environment, the economic system and the policymaking sectors. Since the problem is acutely felt at international level, many countries all over the world have taken effectively pro-active measures, such as the "industrial energy tax", carbon emission trading, enhanced management and control over different sectors etc., aimed at meeting this challenge [2].

The transportation sector (TR) obtains almost 100% of its energy needs from fossil sources, and as such it is one of the major contributors both to energy final use and to GHG emissions. Specifically, the TR, being tightly interrelated with industrial and social development and with the definition of life standards, is responsible for an ever increasing environmental impact: urban air pollution and global warming result from both direct emissions (public and private vehicles, commercial trucks, cars and planes) and indirect emissions (development of traffic infrastructures). Thus, many countries have begun to closely monitor this important sector. The UK government passed a legislation called "Low Carbon Transportation Strategy" in 2009, and proactively took steps to encourage the voluntary adoption of emission reduction measures, set a goal of reduce 14% of carbon emission in traffic sector, and established a transparent monitoring and reporting system; some car manufacturers have signed a voluntary agreement with the European Union (EU) to cut carbon dioxide emissions from new passenger cars to 140 g/km by 2008; transport patterns are being transformed in many countries to encourage walking, cycling and a more systematic use of public transportation. For China, it has been calculated that 7.5% of the total final energy was used in the TR-sector in 2008 [3]. To a certain degree, car ownership pro capite is presently low compared with that of the developed countries; however, there is a great growth potential on car expenditure in the near future, and hence a correspondingly high potential for critical environmental impact derived from waste gas emission. The Chinese government has recognized the severity of traffic environmental impacts in recent years, and started to pursue steps toward a "greener" transportation system.

In order to formulate appropriate strategies and provide both theory-and-practice based evaluations on reducing environmental impacts, it is necessary to acquire an accurate quantitative assessment of the various waste gases emitted from the TR-sector. A series of researches have been done to gain a more significant understanding of the energy efficiency of the sector and of its environmental impact. In general, the world's transportation system is considered to be unsustainable because automobile use and density has strongly increased during the last few decades [4]. However, Richardson [5] suggested to turn down this statement, and considered that transportation systems enable a large number of people to access and exploit economic and social opportunities necessary for life maintaining. An assessment of energy utilization and waste gas emission in the TR-sector can be conducted along two main lines of thought: first, a quantitative estimation of energy depletion and environmental emission [6] can be sought after on the basis of energy, emergy and/or exergy efficiency indicators [7,8]. This kind of approach leads to a prescription about macroscopical energy and exergy flow diagrams or about a "desirable" life cycle process [9,10]: several applications to different countries, areas or social units have been published [7,11–17]. The second line of thought concentrates on the comprehensive impact of social, economical, ecological and political aspects within a sustainable perspective [18,19]: statistical analysis of specific vehicular functions and emissions are related to social development [20], GDP [21], global commercial activity [22], quality of public life [23], environmental emissions [24], strategies and solutions [25] and so on.

For a more precise and profound recognition of transportation's effects on human society, including ecological and sociological perspective and maintaining an intrinsic physical quality, the concept of exergy paves the way towards the development of a reasonably accurate method to estimate the effects of waste emission [8,9,26]. Recall that exergy is defined as the maximum work performed by a system in the process of reaching equilibrium with its reference environment [27–29], and thus constitutes a "thermodynamic measure" of the distance of the state of the system from that of the environment. When evaluating ecological cost, exergy can be regarded as a quantifier combining the quality and quantity of resource consumption and waste emission [30] with a conceptually correct foundation on the second law of thermodynamics. Closely related to use value, exergy analysis, which is a central concept of macroeconomics, has been combined with economics to quantify the cost of the exergy destruction and losses and the cost of artificial activities, thus optimizing various anthropic processes and improving the thermal-economic performances at each stage, thus facilitating downstream decision-making procedure [31–33]. A few applications also dealt with environmental discharges, and demonstrated the potential of exergy analysis as a tool for energy policy making [34,35].

Exergy analysis indeed offers a deep and broad insight into the structure of physical, thermodynamic and ecological costs. However, in view of the intrinsic social expense and "payback" for the sector's operation, which includes a series of activities connecting businesses, accelerating social development and ameliorating life standards, we need a more extensive and inclusive metric. Extended exergy enters the picture here: extended exergy accounting (EEA in the following of this paper), proposed by one of the authors [36,37], is an extension of traditional exergy analysis that expresses the primary production factors, (Labour and Capital, Materials and Energy) in units of "prime resource exergy equivalent", i.e., in kilojoules of primary exergy, and adds another factor, the Environmental Remediation Cost, also expressed in similar units: thus EEA may be regarded as an attempt to bridge the gap about the "production of value" that separates the majority of economists and energists [38,39].

EEA is a socio-economic construct with biophysical references, intended to balance the labor theory of value and the current thermodynamic theory: its quantifier, the extended exergy "cost", can be used as a goal function to optimize the allocation of the involved "values" (short for "use value" in this paper). Since primary resources, and in particular their exergy, are both the "fuel" for societal development and a "limit" for the carrying capacity of the Earth, EEA can be considered as a proper tool to measure the (exergy) cost of measures aimed at decreasing our degree of unsustainability: it does so not only by displaying the loss of available energy, but also supplying input conditions and allocations, for "more sustainable" solutions may in some cases require greater resource consumption than "less sustainable" ones [40]. Furthermore, new light is shed by EEA on the so-called "environmental externalities" problem, in that this theory augments the "cost" of the internal irreversibility of a system by charging its products with the remediation cost of its waste emissions.

This study presents an extended exergy analysis of the TR-sector in China to investigate the status of materials and energy use, social and economical input, and the environmental impact of waste gas discharge. Historically a bottleneck in the economic and social development of China, the transportation situation has been greatly improved in the last decade. By the end of 2008, the total highways length open to traffic had reached to 3.86 million km, of which expressway amounted to 65,000 km. The length of railways

in operation totaled 79,687.3 km; the length of navigable island waterways was 122,763 km; the length of civil aviation route amounted to 2.46 million km in total. Transportation in rural areas, formerly non-motorized (bicycles, cycle cars, various forms of animal power, with people traveling largely on foot), has undergone great systemic improvement, with more than 90% of the rural residents having access to nearby highways by the end of 2008 [41,42]. According to the classification presented in the Yearbook of China Transportation and Communications (YCTC) of 2009 [41], the Chinese TR-sector consists of four sub-sectors (transportation modes): highway, railway, waterway and air. Pipeline transport is excluded in this analysis, due to its very limited scale.

2. Methods and data

The EEA method has been first formulated in 1998 and subsequently refined and completed in a series of publications, dealing with different theoretical study and social applications [36–39,43]. This method assigns an extended exergy (EE) measure to labor and capital fluxes in addition to thermomechanical and chemical exergy values. The definition of EE is:

$$EE = CEC + E_K + E_L + E_R \tag{1}$$

where *CEC* represents the cumulative exergy consumption, E_K is the exergy equivalent of monetary flows, E_L is the exergy equivalent of human labor, and E_R stands for the environmental impact or remediation cost.

2.1. Natural resource exergy consumed in TR-sector

In Eq. (1), *CEC* expresses the equivalent total net resource input (renewable or not) measured in exergy units. The data for the TR-sector have been extracted from [42]: from a consumption viewpoint, all the input in this part are either electricity or fossil fuels, namely, coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, and natural gas. Furthermore, the natural exergy consumed in manufactured goods of transport equipments (such as vehicles, batteries, engines, airplanes, etc.) in that very year is also included as exergy flows from Industrial sector into TR-sector. Exergy factors of fossil fuels were taken from [44].

2.2. Labor and capital exergy

In EEA, E_{in} (the global influx of exergy resources) is primarily used to sustain all of the individuals participating of the Society in order to generate labor, and another exergy flux which is used to generate the monetary circulation M2. Therefore, we can write:

$$E_L = \alpha E_{in} \tag{2}$$

$$E_K = \beta E_L \tag{3}$$

In [35,45–49,50] the expressions for α and β are:

$$\alpha = \frac{f e_{sure} N_h}{E_{in}} \tag{4}$$

$$\beta = \frac{M2}{s N_W W} \tag{5}$$

the significance of the parameters in Eqs. (4) and (5) are illustrated in Table 1: notice that α and β are econometric factors that can be independently calculated for each society under examination.

A clarification is necessary here: a large portion of the M2 in China is time deposits and saving deposits, which is not the monetary circulation mode in accordance with those of the western bank system, and also checks cannot be freely cashed as it is in the western countries. Therefore, and only for this reason, we were forced to take the GDP as the monetary circulation indicator, though it is clear that (a) its numerical value is different from the real monetary circulation and (b) even conceptually the GDP is not a correct indicator of monetary circulation, because it merely represents the monetary measure of the goods and services generated, imported and exported.

2.3. Extended exergy of environmental remediation

To quantify the total environmental impact associated with the waste emission, EEA introduces the concept of an "ideal treatment process" that separately processes each emitted substance *j* and releases it into the environment at "zero exergy", i.e. at p_0, T_0 and at its average concentration in the environment itself, $c_{j,0}$. To do this, a suitable process is selected, and its extended exergy input in materials, energy, labor and capital is computed: the additional "resource expense" is the cost of the environmental externality. The most harmful elements in waste gas emission are CO, NOx and SO_2, because they are noxious for human healthy, flora and fauna's growth. Besides, they will lead to photochemical smog under certain circumstance. So we chose these three types of waste gases as "environmental externalities". In this study, the following processes were selected:

(a) for CO, post-combustion: $CO + O_2 = CO_2$,
(b) for NOx, catalytic reduction: $2NOx = xO_2 + N_2$ and
(c) for SO_2, calcination: $SO_2 + CaO + 0.5O_2 = CaSO_4$.

There is a large database of both theoretical and experimental results for these treatments, and their exergy input is well known in terms of materials and energy input. Labor and capital data have been taken from [53], and the results are displayed in Table 2. In this approach, it is obviously necessary to calculate the chemical exergy of the untreated pollutants: recall that the chemical exergy of a single-phase gaseous substance is the minimum work to bring

Table 1
List of the parameters U/used in the evaluation of α and β.

Parameter	Unit	Meaning	Value	Source
f	/	Correction factor (f=HDI/HDI$_0$)	13.75	[51]
e_{sure}	J/(person × day)	Exergy consumption amplification × exergy consumption for survival	$10^7 J$	[31,35,45–47]
$\boldsymbol{N_h}$	/	Population	1.33×10^9	[41]
$\boldsymbol{E_{in}}$	J/yr	Exergy influx input to the society	87.85 EJ	[15,48,49]
M2	\$/yr	Money+quasi-money circulation	≈ GDP (4.52×10^{12}\$)	[41,48,50]
S	\$/(person × yr)	Average wage	4.61×10^3\$	[52]
$\boldsymbol{N_W}$	/	Number of workers	639.5×10^6 (27.3% female)	[52]
W	Workhours/(person × yr)	Average workload	244 for male, 223 for female	[52]

Note: HDI refers to Human Development Index, it is published by United Nations Development Program every year. HDI can measure the level of economic and social development within United Nations Member States. HDI$_0$=0.055 [51], HDI$_{2007,\ China}$=0.756.

Table 2
Specific chemical exergy (SCEx) of waste gas emissions and extended exergy of remediation (EE_{env}) for waste gas emissions associated with fossil fuel consumption of the vehicles.

Waste gas	SCEx (kJ/kg)	EE_{env} (kJ/kg)
CO	9825.0	1.18×10^4
NOx	2963.3	3.61×10^3
SO_2	4892.3	5.89×10^3

Table 3
Average miles for i.c.e. vehicles in 2008 in China.

Vehicle type	**HDGV**	**MDGV**	**LDGV**	**MGV**	**HDDV**	**MDDV**	**LDDV**	**MDV**	**MC**
AM (10^4 km)	2.4	2.6	3.2	3.9	2.4	2.7	3.9	3.9	3.9

Table 4
A general average composition of the coal mixture.

C	H	S	O	N	A (ash)	W (water)
60%	4%	3.5%	9%	1.5%	12%	10%

Table 5
Emission factors of different vehicles in China.

Vehicle type	*EF*		
	CO (g/km)	NOx (g/km)	SO_2 (kg/t)
Highways			
HDGV	5.63	9.56	2.00
MDGV	2.67	4.66	2.00
LDGV	2.61	2.75	2.00
MGV	2.61	2.75	2.00
HDDV	86.62	24.1	2.80
MDDV	73.67	2.58	2.80
LDDV	41.11	2.39	2.80
MDV	41.11	2.39	2.80
MC	48.04	1.79	2.00
	CO (kg/t)	NOx (kg/t)	SO_2 (kg/t)
Railways			
Steam locomotives	12.61	32.14	70.00
Diesel locomotives	7.06	50.29	2.16
	CO (g/tkm)	NOx (g/tkm)	SO_2 (g/tkm)
Waterways	0.12	0.40	0.05
Civil aviation	14.00	5.55	0.62

the gas (already at p_0, T_0) into chemical equilibrium with the corresponding component in the reference environment. To account for the chemical exergy of the three gases considered here, the globally averaged model of the standard atmosphere defined by Morris and Szargut [58] is used. Therefore, we applied the specific chemical exergy (SCEx) values listed in Table 2 to main waste gases of CO, NOx, SO_2 in TR-sector, omitting other minor components: all three gases were associated with fossil fuel consumption by the vehicles [54].

To complete the calculation, it is necessary to calculate the specific mass of waste gas discharge separately for each different sub-sector of TR. A generally accepted method is as follows:

for i.c.e. powered vehicles:

$$m = EF(g/\text{km}) \times AM(t/\text{year}/\text{vehicle}) \times n(\text{year vehicle}) \quad (6)$$

Table 6
Statistic of different types of vehicle [1].

Vehicle type	Number	Diesel vehicles	Gasoline vehicles	$AM\times n$ (t)[Note 1]
HDCV	1,003,939	173,681	830,258	2.18×10^6
MDCV	1,431,889	247,717	1,184,172	3.13×10^6
LDCV	32,711,443	5,659,080	27,052,363	3.03×10^7
MCV	3,241,949	560,857	2,681,092	2.52×10^6
HDVV	2,008,360	1,051,376	956,984	3.27×10^9
MDVV	2,497,305	1,307,339	1,189,966	4.97×10^9
LDVV	6,449,561	3,376,345	3,073,216	1.07×10^{11}
MVV	305,430	159,893	145,537	6.32×10^9
MB	1,346,218	/	/	4.99×10^9

The detail calculations are shown in Table 7.

for railways:

$$m = EF(\text{kg}/t) \times ERC(t/\text{year}/\text{vehicle}) \times n(\text{year vehicle}) \quad (7)$$

for waterways and civil aviation:

$$m = EF(g/\text{tkm}) \times CT(\text{t km}/\text{year}/\text{vehicle}) \times n(\text{year vehicle}) \quad (8)$$

where m represents the total amount of waste gas, *EF* is the available emission factor, and n is the total fleet size of each transportation mode. *AM*, *ERC* and *CT* are average miles per mode per year, energy consumption per vehicle per year and total services in terms of ton-kilometer, respectively.

Based on the available data of the average transport distance for passenger and freight in YCTC 2009, as well as on previous relevant studies [15,55], detailed values of average miles for i.c.e. powered vehicles are reported in Table 3.

Table 4 shows the emission factors of vehicles in China for year 2004 [15]. To better understand the different forms of emissions, we divided i.c.e. vehicles into nine types based on the comprehensive study presented in [55]: heavy-duty (HDGV), medium-duty (MDGV), light-duty (LDGV) and mini gasoline vehicles (MGV); heavy-duty (HDDV), medium-duty (MDDV), light-duty (LDDV) and mini diesel vehicles (MDV); and mini cars (MC). The specific values of emission factors with different vehicles were listed in Table 5.

For the railway system, the *EF* of CO, NOx, and SO_2 from diesel locomotives are taken from [56]. The gas emissions of steam locomotives are mainly due to the combustion of coal and, according to [15] (see Table 4), a general average composition of the coal mixture was used. The *EF* of steam locomotives are calculated based on the assumption that S is totally transformed to SO_2 and N is completely to NOx. The indirect environmental emission from electricity generation is also included in these calculations [54], by considering the waste gases from electricity consumed within the transportation system boundary.

When accounting the i.c.e. powered vehicles emission, the different types of cars and vans must be accounted for. In Table 6 of the Year Book of China Transportation & Communications, nine main kinds of vehicles are listed: heavy-duty carriage vehicles (HDCV), middle-duty carriage vehicles (MDCV), light-duty carriage vehicles (LDCV), mini carriage vehicles (MCV), heavy-duty van vehicles (HDVV), middle-duty van vehicles (MDVV), light-duty van vehicles (LDVV), minivan vehicles (MVV), and other vehicles (mainly referred to MB). The distribution of diesel and gasoline vehicles was also accounted for: the percentage of diesel trucks is 13.70%; and the percentage of diesel buses 52.35% [57]. The integrated results are shown in Tables 7 and 8, which is based on the outcome of Table 6.

When we evaluate the extended exergy of environmental remediation, the indirect emission from electricity generation should be inclusively considered. In China, electricity production mainly has four types of source, hydropower, thermal power,

Table 7
The detail calculations of different types of vehicle.

Vehicle type	Fuel consumption (l/(100 km))	Number of vehicles	*AM* (10,000 km)	$AM \times n$ (t)
HDDCV	11.2	173,681.447	2.4	3.97×10^5
HDDVV	8.3	1,051,376.46	2.4	1.78×10^6
MDDCV	11.2	247,716.797	2.7	6.37×10^5
MCCVV	8.3	1,307,339.17	2.7	2.49×10^6
LDDCV	11.2	5,659,079.64	3.9	2.10×10^7
LDDVV	8.3	3,376,345.18	3.9	9.29×10^6
MDCV	11.2	560,857.177	3.9	2.08×10^6
MDVV	8.3	159,892.605	3.9	4.40×10^5
HDGCV	13.1	830,257.553	2.4	1.89×10^9
HDGVV	8.3	956,983.54	2.4	1.38×10^9
MDGCV	13.1	1,184,172.2	2.7	3.04×10^9
MDGVV	8.3	1,189,965.83	2.7	1.93×10^9
LDGCV	13.1	27,052,363.4	3.9	1.00×10^{11}
LDGVV	8.3	3,073,215.82	3.9	7.21×10^9
MGCV	13.1	2,681,091.82	2.4	6.11×10^9
MGVV	8.3	145,537.395	2.4	2.10×10^8
MC	13.1	1,346,218	3.9	4.99×10^9

Note 1: Assume that all MC consume gasoline in China in this paper, and omit tiny minority new energy MC pattern.

Table 8
Statistic of different types of vehicle [2].

Vehicle type	Calculation process[Note 2]	Number
HDGV	HDDCV + HDDVV	1,225,058
MDGV	MDDCV + MDDVV	1,555,056
LDGV	LDDCV + LDDVV	9,035,425
MGV	MDCV + MDVV	720,750
HDDV	HDGCV + HDGVV	1,787,241
MDDV	MGDCV + MDGVV	2,374,138
LDDV	LGDCV + LDGVV	30,125,579
MDV	MGCV + MGVV	2,826,629
MC	MC	1,346,218

Note 2:
- high-duty diesel carriage vehicles—HDDCV,
- middle-duty diesel carriage vehicles—MDDCV,
- light-duty diesel carriage vehicles—LDDCV,
- mini diesel carriage vehicles—MDCV,
- high-duty gasoline carriage vehicles—HDGCV,
- middle-duty gasoline carriage vehicles—MGDCV,
- light-duty gasoline carriage vehicles—LGDCV,
- mini gasoline carriage vehicles—MGCV,
- high-duty diesel van vehicles—HDDVV,
- middle-duty diesel van vehicles—MDDVV,
- light-duty diesel van vehicles—LDDVV,
- mini diesel van vehicles—MDVV,
- high-duty gasoline van vehicles—HDGVV,
- middle-duty gasoline van vehicles—MDGVV,
- light-duty gasoline van vehicles—LDGVV and
- mini gasoline van vehicles—MGVV.

Table 9
Parameters used in waste gases emission of electricity in TR-sector.

Parameter	Unit	Sign	Value
Consumption of SCE	t	B	4.31×10^4
Sulfur content in coal	%	S	0.44
Nitrogen content in coal	%	n	1.5
Combustible sulfur content in coal	%	K	80
Desulfuration rate	%	ηs	0
Conversion rate from N-fuel to NO-fuel	%	β	20
Amount of burned gas per kilogram fuse	m^3/kg	V_y	10
NO concentration in burning time	mg/Nm^3	G_{NOx}	93.8

nuclear power, and imports. Electricity from thermal power took up 80.8% in 2008 [41], the average coal generating efficiency was 33% in China [58], and Tr-sector consumed 571.82×10^2 million kWh, the

Table 10
Primary exergy consumed in manufacturing of transport equipment and TR-sector in 2008.

Fuel forms	Mass	
	Manufacture of transport equipment	Transport, storage and post process
Coal	741.55 (10^4 t)	685.45 (10^4 t)
Coke	116.41 (10^4 t)	0.55 (10^4 t)
Crude oil	0.11 (10^4 t)	163.66 (10^4 t)
Gasoline	45.21 (10^4 t)	2763.19 (10^4 t)
Kerosene	7.57 (10^4 t)	1129.98 (10^4 t)
Diesel oil	61.99 (10^4 t)	6794.36 (10^4 t)
Fuel oil	12.21 (10^4 t)	1389.95 (10^4 t)
Natural gas	7.15 (100 million m^3)	16.89 (100 million m^3)
Electricity	424.08 (100 million kWh)	531.91 (100 million kWh)
Total energy	2376.93 (10^4 t of SCE)	20643.37 (10^4 t of SCE)
Total exergy	4.00×10^{17} (J)	4.58×10^{18} (J)

Table 11
Primary exergy input per sub-sector.

Way type	Percentage (%)[Note 3]	Exergy (J)
Total vehicle	100	4.98×10^{18}
Highway	61.60	3.07×10^{18}
Railway	10.56	5.26×10^{17}
Waterways	17.37	8.65×10^{17}
Civil aviation	10.47	5.21×10^{17}

Note 3: All the percentages from the recent research were calculated by Zhou in 2010 [60].

Table 12
The labor, capital and environmental exergy in TR-sector in China (2008).

Vehicle type	Labor exergy (J)	Capital exergy (J)	Environmental emission exergy (J)
Total	1.09×10^{18}	8.07×10^{17}	2.24×10^{18}
Highways	5.53×10^{17}	4.82×10^{17}	2.22×10^{18}
Railways	3.87×10^{17}	2.26×10^{17}	3.21×10^{15}
Waterways	9.74×10^{16}	6.68×10^{16}	1.31×10^{16}
Civil aviation	5.66×10^{16}	3.27×10^{16}	1.88×10^{15}

amounts of waste gases emission contained in used electricity in Tr-sector are calculated as follow [59]:

$$G_{SO_2} = 1.6 \times B \times 10^3 \times S(1 - \eta s) \tag{9}$$

G_{SO_2} refers to SO_2 emission, kg; B is the consumption of SCE, t; S is sulfur content in coal; and ηs is desulfuration rate, %.

$$G_{CO} = 2330qCB \tag{10}$$

G_{CO} refers to CO emission, kg; q is the imperfect combustion rate, %; C is the carbon content, %; and B is the consumption of SCE, t. In average, 0.23 kg CO will be emitted by combusting 1 t of coal.

$$G_{CO} = 0.23B \tag{11}$$

$$G_{NOx} = 1.63 \times B \times 10^3 \times (\beta \times n + 10^{-6} \times V_y \times C_{NOx}) \tag{12}$$

G_{NOx} refers to NOx emission, kg; B is the consumption of SCE, t; β is conversion rate from N-fuel to NO-fuel, %; n is the Nitrogen content in coal, %; V_y is the amount of burned gas per kilogram fuel, Nm^3/kg; and C_{NOx} is NOx concentration during combustion. All the parameters used in waste gases emission of electricity in TR-sector are collected in Table 9.

3. Results

3.1. Natural resource exergy consumed in TR-sector

From [3,41] the exergy inputs in the TR-sector and its sub-sectors are listed and calculated here (see Tables 10 and 11).

3.2. Labor, capital and environmental exergy in TR-sector

Based on the available data on the investment in fixed assets as well as the number of workers in the TR-sector [42], and the parameters listed in Table 2, we finally obtain the extended exergy equivalents of labor, capital and direct environmental emission (see Table 12).

Electricity production in China has four types of source, hydropower, thermal power, nuclear power, and imports. Electricity from thermal power constituted 80.8% of the total generation in 2008 [41], the average coal plant generating efficiency was 33% [60], and the TR-sector consumed 571.82 $\times$ 10^2 million kWh. The amount of waste gases emission caused by the electricity use in the TR-sector is calculated and listed in Table 13.

The direct and indirect emission of waste gases in TR-sector were then used to calculate the EE_{env} displayed in Table 14.

Table 13
Environmental indirect-emission exergy contained in electricity generation from conversion sector.

	Consumption units	Total consumption	Exergy (J)
Electricity used in TR-sector	10^8 kWh	531.91	–
Coal-generated electricity	10^8 kWh	429.78	–
Coal	1 million t of SCE	1.55	2.61×10^{18}
SO_2 emission	1 kg	3.03×10^7	1.48×10^{14}
CO emission	1 kg	9.91×10^3	9.74×10^{10}
NOx emission	1 kg	2.11×10^8	8.21×10^{10}

Table 14
EE_{env} for total waste gas emissions associated with fossil fuel consumption in the TR-sector.

	CO (kg)	NOx (kg)	SO_2 (kg)
Highways	4.92×10^{10}	4.55×10^9	3.52×10^{11}
Railways	9.88×10^7	7.04×10^8	3.02×10^7
Waterways	6.03×10^8	2.01×10^9	2.51×10^8
Civil aviation	1.67×10^8	6.58×10^7	7.42×10^6
Electricity emission	3.57×10^6	7.58×10^{11}	1.09×10^{10}
Total above	5.01×10^{10}	7.65×10^{11}	3.63×10^{11}
EE_{env} (J)	5.91×10^{17}	2.76×10^{18}	2.14×10^{18}

3.3. Extended exergy analysis of the TR-sector

Fig. 1 clearly shows that highways transport is the most exergy depleting sub-sector, taking up 76.06% of the total extended sectoral exergy input (see Fig. 2). Furthermore, material- and environmental exergy were the two major contributors with 42.16% and 41.74%, respectively, to the total exergy (see Fig. 3). Capital and labor exergy contributions were not as large as that of

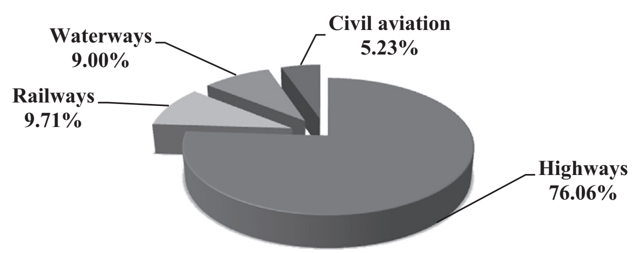

Fig. 2. Extended exergy consumption in four transportation modes in China (2008).

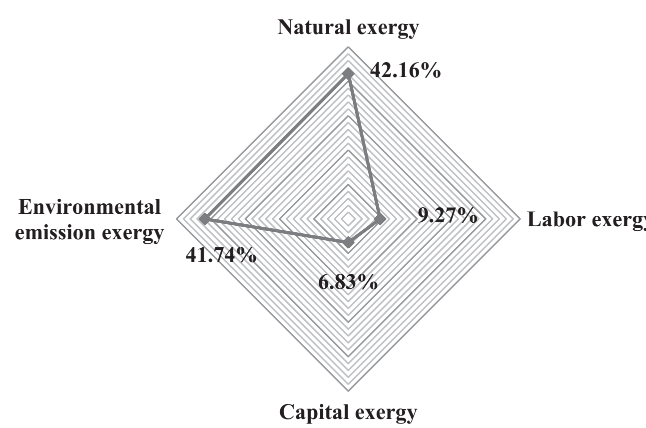

Fig. 3. Four kinds of exergy contribution in extended exergy consumption in TR-sector in China (2008).

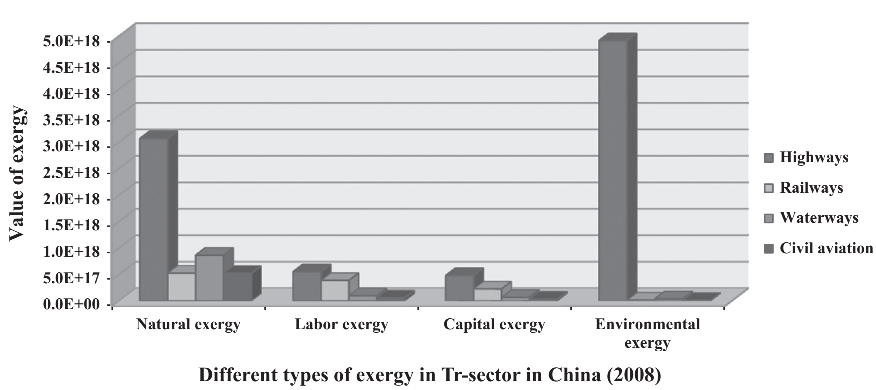

Fig. 1. Extended exergy distribution of different vehicle types in the TR-sector in China (2008).

Table 15
The distribution of waste gas emission and remediation exergy in four kinds of vehicles in the TR-sector and indirect exergy from electricity generation in China (2008).

Items	Emission exergy						Total environment exergy (kJ)	
	CO (kJ)	%	NOx (kJ)	%	SO_2 (kJ)	%	Emission	Remediation
Highways	4.83×10^{14}	98.26	1.35×10^{13}	62.05	1.72×10^{15}	99.92	2.22×10^{15}	2.67×10^{15}
Railways	9.71×10^{11}	0.20	2.09×10^{12}	9.61	1.48×10^{11}	0.01	3.21×10^{12}	3.89×10^{12}
Waterways	5.93×10^{12}	1.20	5.96×10^{12}	27.44	1.23×10^{12}	0.07	1.31×10^{13}	1.58×10^{13}
Civil aviation	1.65×10^{12}	0.33	1.95×10^{11}	0.90	3.63×10^{10}	0.00	1.88×10^{12}	2.25×10^{12}
Total vehicle	4.92×10^{14}	/	2.17×10^{13}	/	1.72×10^{15}	/	2.24×10^{15}	2.69×10^{15}
Electricity	9.74×10^{7}	/	8.21×10^{7}	/	1.48×10^{11}	/	1.48×10^{11}	9.40×10^{11}
Total	4.92×10^{14}		2.20×10^{13}		1.77×10^{15}		2.24×10^{15}	2.69×10^{15}

Table 16
The value of ME/EE with different types of vehicle in the TR-sector.

	Highways	Railways	Waterways	Civil aviation	Total vehicle
EE/ME	1.60	0.02	0.04	0.02	0.99

material- and environmental equivalent exergy, but took up more than 16% of total extended exergy consumption in TR-sector.

From the viewpoint of waste gas emission, highway vehicles were by far the largest contributor to the direct emission source (see Table 15), with 98.26% of total CO, 62.05% NOx, and 99.92% of SO_2. As a consequence of the large growth rate of the Chinese economy, more and more highway vehicles are put into service every year: thus, this is a structural problem that needs to be addressed. A statistical analysis (discussed in Appendix A) revealed that LDGV and LDDV generated the lion's share of waste gas emissions. For the electricity use that was allocated to the TR-sector as an input from the conversion sector, the indirect emission from the power plants was mainly due to SO_2. For fossil fuels are the dominant energy source in the TR-sector, monitoring/controlling/reducing the direct environmental exergy emission from road transport particularly i.c.e. powered vehicles appears as the most effective measure towards decreasing the sectoral environmental impact.

Finally, a comparison of consumed material exergy (ME) and total environmental exergy (EE) in the TR-sector for different types of vehicle is shown in Table 16. It is obvious that in China the highway is the most environmental unfriendly transportation mode, not only due to its natural very high primary resource input (Fig. 1), but also because of its high environmental damage intensity (environmental disturbance after resource depletion). Table 16 shows that the latter is 80 times higher than that of railways and civil aviation, and 40 times higher than that of waterways′.

4. Conclusions

As a scientific and objective measure for material resource input, labor and capital expenditures and physical environmental impact, the thermodynamic concept of extended exergy is introduced to unify the assessment of main natural, manpower, economic and ecological cost from fossil fuel consumption process in the Chinese transportation system in 2008. The four contributions to extended exergy were presented for different types of vehicle, and the results show that highways consumed the highest share of extended exergy, and also that primary resources- and environmental remediation were the two major components of extended exergy, implying that the destructive influence on the environment has the same quantitative significance as that of the consumption of non-renewable materials.

In terms of emissions, exergy from energy consumption, railways, waterways and civil aviation are all generating lower amounts of waste gas with that of highways. However, each of these three modes has apparent disadvantages. For example, all of them are more applicable to long distance transport, low time efficiency for the former two, and high economic cost for the latter one constituting the effective limits. A point that clearly emerges from our study is that it is necessary to construct a higher level evaluation criterion to rank these transportation modes, and that, from the point of view of primary resource exergy consumption, highways is the most unsustainable way.

Therefore, in order to reduce ecological expense from gas emission, it is urgent to develop urban rail transit between and within cities, replace fossil fuels by electrical energy, solar energy and other clean energy, limit urban short-trip transportation missions, lower or bounty the airplane fee by government and airline companies to encourage using this mode for longer trips, and make all modes more environmental friendly. Moreover, to impose a "resource and environment tax" from private i.c.e. powered vehicles users should be considered by government, both as a short-term measure to reduce pollution and as a long-run promoter of a revolution towards ecologically healthier transportation.

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Appendix A. Environmental emission exergy for four types of vehicle

For highways:

Vehicle type	*EF*			$AM \times n$ (t)			$AM \times n$ (t)		
Highways	CO (g/km)	NOx (g/km)	SO_2 (kg/t)	CO (g)	NOx (g)	SO_2 (kg)	CO (kJ)	NOx (kJ)	SO_2 (kJ)
HDGV	5.63	9.56	2	1.38×10^{11}	2.34×10^{11}	4.35×10^{6}	1.36×10^{12}	6.94×10^{11}	2.13×10^{10}
MDGV	2.67	4.66	2	8.30×10^{10}	1.45×10^{11}	6.25×10^{6}	8.16×10^{11}	4.29×10^{11}	3.06×10^{10}
LDGV	2.61	2.75	2	4.72×10^{11}	4.97×10^{11}	6.06×10^{6}	4.63×10^{12}	1.47×10^{12}	2.96×10^{11}
MGV	2.61	2.75	2	3.76×10^{10}	3.96×10^{10}	5.04×10^{6}	3.70×10^{11}	1.17×10^{11}	2.47×10^{10}
HDDV	86.62	24.1	2.8	4.33×10^{12}	1.21×10^{12}	9.17×10^{9}	4.26×10^{13}	3.57×10^{12}	4.49×10^{13}
MDDV	73.67	2.58	2.8	4.90×10^{12}	1.72×10^{11}	1.39×10^{10}	4.81×10^{13}	5.08×10^{11}	6.81×10^{13}
LDDV	41.11	2.39	2.8	3.47×10^{13}	2.02×10^{12}	3.01×10^{11}	3.41×10^{14}	5.97×10^{12}	1.47×10^{15}
MDV	41.11	2.39	2.8	3.25×10^{12}	1.89×10^{11}	1.77×10^{10}	3.20×10^{13}	5.61×10^{11}	8.66×10^{13}
MC	48.04	1.79	2	1.29×10^{12}	4.82×10^{10}	9.97×10^{9}	1.27×10^{13}	1.43×10^{11}	4.88×10^{13}

For railways:

In YBCTC 2009 [1], total freight ton-kilometers for railways in 2008 was 2.51063×10^6 million t-km, in which 65.2% were diesel locomotives, 34.8% were electrical locomotives, moreover, the total energy consuming workload per vehicle was 5.6 tce/(million t-km) [2].

$$m = EF(\text{kg}/t) \times ERC(t/\text{year/vehicle}) \times n(\text{year vehicle})$$

$$ERC \times n = (2.51063 \times 10^6 \text{ million } t - \text{km}) \times 5.6 \text{ tce}/(\text{million } t - \text{km}) = 1.4 \times 10^7 \text{ tce}$$

Vehicle type	*EF*	$ERC \times n$ (tcn)	Waste gas emission (g)	Emission exergy	Vehicle type			*EF*		
Railways	CO (kg/t)	NOx (kg/t)	SO_2 (kg/t)		CO (kg)	NOx (kg)	SO_2 (kg)	CO (kJ)	NOx (kJ)	SO_2 (kJ)
Steam locomotives	12.61	32.14	70	/						
Diesel locomotives	7.06	50.29	2.16	1.40×10^{7}	9.88×10^{7}	7.04×10^{8}	3.02×10^{7}	9.71×10^{11}	2.09×10^{12}	1.48×10^{11}

For weaterways and civil aviation:

Vehicle type	*EF*			Total freight ton-kilometers (100 million t-km)	$CT \times n$ (tkm)	Wast gas emission (g)			Emission exergy		
	CO (g/tkm)	NOx (g/tkm)	SO_2 (g/tkm)	/	/	CO (g)	NOx (g)	SO_2 (g)	CO (kJ)	NOx (kJ)	SO_2 (kJ)
Waterways	0.12	0.4	0.05	50,262.7	5.03×10^{12}	6.03×10^{11}	2.01×10^{12}	2.51×10^{11}	5.93×10^{12}	5.96×10^{12}	1.23×10^{12}
Civil aviation	14	5.5	0.62	119.6	1.20×10^{10}	1.67×10^{11}	6.58×10^{10}	7.42×10^{9}	1.65×10^{12}	1.95×10^{11}	3.63×10^{10}

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